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Exploration of Blockchain-Based Building Energy Management

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Abstract: With the increasing urbanization in China, building energy consumption gradually becomes a significant portion of overall energy use, necessitating resource conservation and reduced building energy consumption to develop green buildings. Public buildings have high energy consumption density, presenting substantial energy-saving potential. Among various attempts at energy saving, blockchain technology is gaining attention. This paper explores the application of blockchain technology in building energy management, issuing smart contracts with energy-saving targets to employees in public buildings. Employees commit to and implement energy-saving actions to achieve these goals, receiving rewards to incentivize these behaviors, thereby promoting the creation of green buildings, efficient energy management, and the cultivation of energy-saving potential.

1. Introduction

With the rise in urbanization, large-scale urban construction, and increasing demand for residential comfort in China, per capita building area and the number of energy-consuming equipment are growing, making building energy consumption a critical part of China's energy use, accounting for 27.6% and continuing to rise [1]. Currently, urban residential buildings consume about 25% of the total electricity generated in China [1], while building energy consumption makes up around 28% of terminal energy use [2]. Saving resources, reducing energy consumption, and building green buildings should not be delayed. Public buildings, as high-density energy consumers, offer significant potential for energy savings. This paper explores blockchain technology in building energy management, constructing green buildings, enhancing energy efficiency, and tapping into energy-saving potential without compromising living comfort.

2. Current Status of Energy Conservation in International & Chinese Public Buildings

2.1. Current Status of International Energy Conservation

Many Western countries are at the forefront of public building energy consumption statistics. In 1976, the UK conducted an energy consumption survey, creating a detailed database including building type, air conditioning type, etc. [2]. The German government established an independent regulatory body to oversee energy conservation and emission reduction in production and transportation sectors [3]. Currently, the US has established two widely used databases for building energy use, the Department of Energy’s Commercial Buildings Energy Consumption Survey (CBECS) and California's Commercial End-Use Survey (CEUS), with the National Institute of Standards and Technology (NIST) responsible for compiling the statistics.

There have been attempts to integrate smart contracts into building energy conservation. Khatoon et al. [4] provided a blockchain-based smart contract system targeting key issues around trading energy efficiency savings, accurately estimating savings, ensuring data transparency among stakeholders, and improving inefficient administrative processes. Zhao et al. [5] proposed using day-ahead and intraday smart contracts to improve energy efficiency in buildings through collaborative decision-making, autonomous transactions, and billing, thus reducing the cost of distributed energy dispatching. Hahn et al. [6] introduced a smart contract for transactive energy auctions, using blockchain to establish trust without a central authority, implementing a Vickrey auction to ensure honest bids, facilitating efficient energy exchange among prosumers, and enhancing energy savings.

2.2. Current Status of Energy Conservation in China

The prerequisite for public building energy conservation is understanding the specific situation of building energy use. Since 1986, China has implemented a "three-step energy conservation" strategy: first, achieving a 30% energy-saving rate based on local standard heating energy consumption baselines, second, increasing the rate to 50%, third, ultimately reaching a cumulative 65% energy-saving rate. However, even after completing these steps, China's building heat consumption index remains 50% higher than that of developed countries with similar climate conditions [7]. Since 2013, the government has monitored energy consumption in public and government buildings, establishing total energy consumption standards for buildings. Yet, the widespread issues of lights left on, and air conditioning operating around the clock in many public and government buildings persist. The "Beijing Energy Conservation Implementation Plan (2023)" mandates that government agencies and state-owned enterprises lead by example in managing exterior building lighting, reducing landscape lighting intensity, and shortening usage times. It calls for optimized lighting in lobbies, corridors, restrooms, and elevators, maximizing natural light and using sensors to eliminate unnecessary daytime lighting. Lights should be turned off after meetings or work hours to prevent overuse. Indoor temperatures must comply with public building standards, and underground garages should generally not be heated or cooled. Where possible, air conditioning should be turned off before leaving the office. The energy consumption data collected by the building energy monitoring system shows a significant positive deviation from the actual data, and there remain security risks until blockchain technology can guarantee the accuracy. Additionally, public and government buildings are managed by various decentralized departments and offices, lacking specific responsible entities, making it difficult to enforce energy conservation management in employees’ daily behaviors.

As blockchain-based smart contracts have not yet been applied in the field of building energy conservation, relevant research and practice in China remain a blank slate. This paper is the first to introduce blockchain technology, particularly smart contracts, into building energy management, aiming to create an innovative and more efficient energy-saving framework, filling the gap in this field and promoting its development.

3. The Application of Blockchain in Building Energy Conservation

In the realm of the Internet of Things, blockchain technology mainly addresses trust and data security issues, offering services such as trusted storage, data encryption, access control, and identity authentication [8]. With features like decentralization, transparency, automatic contract execution, and traceability [9], it provides an automated and efficient application environment for building energy conservation.

3.1. Distributed Energy Trading

Implementing building energy conservation often involves using more distributed energy sources. However, compared to traditional energy trading, distributed energy trading has lower entry barriers, lacks transparency, and has risks due to its inherent uncertainties [10]. Moreover, the unpredictability in the output of distributed energy sources and the natural self-interest of distributed energy owners leads to frequent problems like fabricating information, manipulating transactions, or discrepancies between the traded and received volumes, potentially destroying trust among trading entities and undermining enthusiasm for distributed energy trading [11].

In academia, there have been attempts to integrate blockchain technology with market models for distributed energy trading: Ping et al. [11] explores a blockchain-based method for managing credit risks in the distributed energy trading market; Li et al. [12] designs a blockchain-based trading solution for distributed energy, and Cai et al. [13] investigates how blockchain technology can be integrated with the market model, system architecture, and execution mechanism of distributed energy trading.

3.2. Building Energy Consumption Data Management

Conversely, there are fewer attempts to combine blockchain technology with building energy monitoring systems. Zeng et al. [14] points out that existing energy monitoring systems still face challenges in areas such as data verification, system security, node trust, processing efficiency, and data sharing, including but not limited to issues like equipment authentication at the data collection end, low data processing efficiency due to lengthy approval processes, data credibility issues due to potential tampering, and data security concerns due to single-node failures, which hinder the full utilization of data value and significantly reduce the effectiveness of energy monitoring and conservation. Blockchain technology effectively addresses these problems. From a data perspective, blockchain technology is essentially a distributed ledger, using chained storage that connects blocks unidirectionally by storing the hash value of adjacent blocks. In monitoring and analyzing building energy consumption, most online energy monitoring systems capable of monitoring and managing energy delivery, distribution, and utilization in government institutions do not have the capabilities offered by blockchain technology: uploading and storing the data collected by each node onto the blockchain, where it is stored in blocks, to be accessed later by other nodes for subsequent analysis and aggregation. The results of these operations can also be stored as blocks, and their inherent immutability ensures the security and accuracy of on-chain information. Specific data operations are conducted in a Merkle tree, where leaf nodes represent data records and non-leaf nodes store the hash values corresponding to their respective leaf nodes. By recursively computing the hash values of leaf nodes and using these as the values for their parent nodes, the process ultimately generates the hash value of the root node, known as the Merkle root. Any attempt to manipulate data would be reflected in the root [15]. Furthermore, any node can access and verify transaction data in real-time, ensuring that detailed energy consumption data, such as indoor temperature, brightness, air conditioning status, and lighting status, are authentic, traceable, and secure, while ensuring it is securely and transparently stored.

4. Overall Framework for Smart Contracts Based on Blockchain Technology in Building Energy Conservation

In the field of building energy conservation, blockchain technology has been successfully applied to distributed energy trading and building energy consumption data management, providing new ideas and solutions for energy savings. However, practical attempts to incorporate smart contracts into energy-saving behaviors are still limited. Traditional building energy-saving processes are incomplete, lacking effective supervision and incentive mechanisms. The response and cooperation of government agencies and individuals in reducing energy consumption are often superficial or merely symbolic. Moreover, individual energy-saving behaviors are difficult to trace and verify, leading to uncertainty and disorder in their implementation.

Thus, this paper explores issuing energy-saving targets to employees through smart contracts, whereby employees respond to those smart contracts and commit to energy-saving actions and receive rewards upon achieving the targets. This approach uses incentives to enforce energy-saving behaviors, aiming to further promote the practice of building energy conservation and provide new ideas and pathways for the development of the field. The new business model constructed based on smart contracts with blockchain technology will clarify responsible entities and establish a complete supervision and reward mechanism based on smart contracts for energy-saving behaviors, making their execution traceable and verifiable. This enables organizations or individuals to respond to energy-saving offers in an orderly manner, forming a positive cycle where rewarded entities and individuals actively participate in building energy conservation, thereby effectively promoting the development of energy-saving initiatives.

4.1. Business Process Analysis

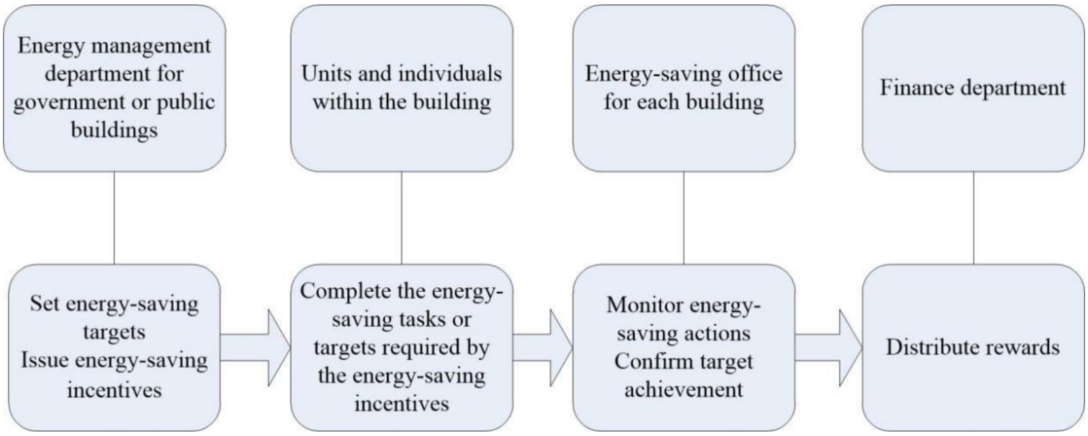

Figure 1: Business process analysis diagram with energy conservation contract as the clue.

Energy Management Department for Government or Public Buildings: Formulates annual or quarterly energy-saving goals and reward mechanisms, and specifies different reward levels and methods corresponding to various energy-saving rates. Rewards can be material, monetary, or honorary, distributed in a tiered manner. The building energy management department then uses blockchain technology to issue energy-saving smart contracts to units or individuals within the building. These contracts specify the energy-saving goals, reward mechanisms, execution conditions, and deadlines, and the department supervises and evaluates the implementation of energy-saving behaviors Figure 1.

Building Units or Individuals: Participate by responding to the blockchain-based contract and implementing energy-saving measures like adjusting air conditioning or optimizing lighting systems, in accordance with the contract requirements. Based on individual energy-saving performance, additional rewards or income can be earned. When energy-saving goals are met, i.e., when energy-saving behaviors align with the conditions specified in the smart contract, the smart contract will automatically execute the corresponding reward mechanism. Energy-saving service evaluations and rewards can be viewed through the blockchain system.

Energy Efficiency Offices for Each Building: Supervise and record energy-saving behaviors. Each energy efficiency office utilizes IoT technology (such as sensor networks) and IoT devices (such as smart meters and temperature sensors) to monitor and record building energy consumption data. They provide real-time supervision of energy-saving behaviors, upload data to the blockchain system to ensure transparency and traceability, and assess the effectiveness of energy-saving measures to ensure the achievement of energy-saving goals. Real-time feedback from IoT devices allows the energy management department to adjust energy-saving strategies based on current data, creating a positive feedback loop.

Finance Department: When energy-saving behaviors meet the requirements of the smart contract, the finance department will manage and settle rewards based on the smart contract. Rewards will be distributed to the units or individuals participating in the energy-saving activities according to the reward mechanism specified in the smart contract. Additionally, records of reward distribution will be recorded on the blockchain to ensure fairness and transparency, encouraging units or individuals who actively participate in energy-saving activities to voluntarily adhere to the terms of the agreement.

4.2. Architecture Design

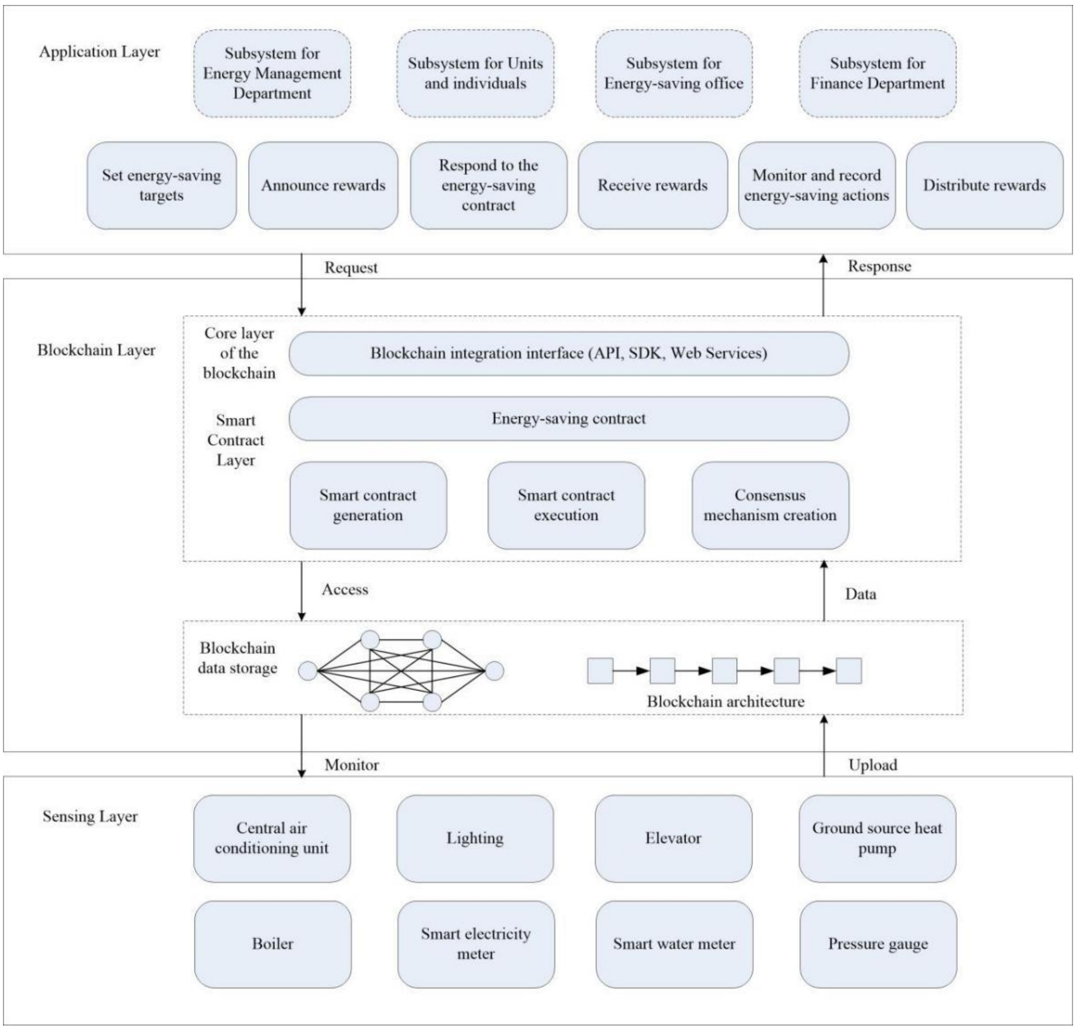

Figure 2: Building energy saving architecture diagram.

The energy management architecture is structured into the following levels Figure 2:

4.2.1. Application Layer

This layer serves various entities: building energy management departments use it to plan energy-saving actions, set goals, define behaviors, and design reward mechanisms, creating and issuing smart contracts for energy management. Entities within public buildings use it to accept and execute energy-saving contracts, furtherly receiving rewards for achieving energy-saving targets. For energy offices in each building, this layer helps them monitor and verify energy-saving behaviors, while finance departments handle reward distribution with its help.

4.2.2. Blockchain Layer

In the system architecture, the blockchain layer primarily consists of the blockchain core layer, the blockchain storage module, and the smart contract layer. The functions of each module are as follows:

Core Blockchain Layer: Provides general services like data management, API interfaces, and device management. It aggregates, accesses, and processes data from sensor networks, including but not limited to energy consumption data and records of energy-saving actions. Additionally, it is responsible for generating smart contracts, recording and verifying energy-saving behaviors, managing rewards, and overseeing the execution of smart contracts.

Smart Contract Layer: Responsible for generating and executing smart contracts. A smart contract is a computer interaction protocol executed according to the terms of a specific contract, referring to an automated programme stored in a blockchain system. It is a kind of coded business logic that can be run automatically, being widely used in distributed systems. The core of smart contracts is to facilitate the alignment of needs among various entities. In this application scenario, the energy-saving department sets energy-saving goals, defines energy-saving behaviors, and delineates areas. Daily, energy-saving contracts are automatically initiated. These smart contracts are broadcast to all nodes, meaning that energy-saving requirements are dispatched to the relevant departments and individuals within specific areas. Units and individuals within the building can respond to these smart contracts to achieve the set energy-saving goals, implement and record the corresponding energy-saving behaviors, and receive rewards. This approach addresses the issues of disordered energy-saving behaviors and unclear responsibilities, thereby enhancing the energy-saving awareness of each node.

Blockchain Storage Layer: Responsible for gathering and storing energy consumption data within buildings (e.g., from meters and temperature sensors), and maintaining contract execution.

4.3. Perception Layer

Includes various sensors and terminal devices deployed within buildings, each functioning as a node in the blockchain network to upload data, like central air conditioning, lighting, elevators, heat pumps, boilers, smart energy meters, and water meters, for real-time energy monitoring.

5. Validation of Energy Saving Contract Effectiveness

To validate the blockchain-based energy-saving contract's effectiveness, a simulated experiment was conducted in a building in Beijing. The building was equipped with uni-and bi-directional meters and other terminals to monitor energy-saving outcomes. The energy office specified energy-saving actions, combined point rewards with public commendations, and published energy-saving contracts, which were responded to by five departments, participating in the incentive mechanism.

In the simulation, Room A achieved the highest energy savings of 14.6%, meeting the set energy reduction target. As a result, the finance department awarded points to Room A and publicly recognized their efforts. This outcome demonstrates that blockchain-based smart contracts can successfully incentivize energy-saving behaviors and promote a culture of energy efficiency within the organization. Overall, the study showed a 10-15% reduction in energy consumption across various rooms, validating the effectiveness of the smart energy management system. (Table 1)

Table 1: Energy-saving performance of five departments responding to energy-saving contracts.

Time Period	Room	Room Function	Starting Energy Consumption (kWh)	Energy Consumption Before Smart Contracts (kWh)	Energy Consumption After Smart Contracts (kWh)	Savings (%)
Week 1	Room A	Meeting Room	500	480	410	14.6%
Week 1	Room B	Office	800	780	700	10.3%
Week 2	Room C	Server Room	1200	1180	1050	11.0%
Week 2	Room D	Cafeteria	600	580	520	10.3%
Week 3	Room E	Rest Area	300	290	260	10.3%
Week 3	Room F	Admin Office	700	680	600	11.8%

6. Conclusion

Public buildings are high-density areas of energy consumption with significant energy-saving potential. This paper presents an innovative building energy management model by integrating blockchain technology, which uses smart contracts to set energy-saving targets, encourages entities or individuals within public buildings to implement energy-saving behaviors, enhances the energy-saving enthusiasm of each entity through incentive mechanisms, and combines with existing energy consumption monitoring systems to create green buildings and improve energy efficiency.

However, this concept lacks practical implementation. Future research should focus on the following areas: First, enhance the verification methods for energy-saving behaviors and strengthen the reliability and security of blockchain technology in practical applications. Second, clearly define the scenarios and redemption mechanisms for reward points to boost employee engagement and enthusiasm. Next, optimize the integration of blockchain technology with existing building energy consumption monitoring systems to ensure data accuracy and authenticity. Furthermore, more refined energy efficiency assessment standards should be developed to make the evaluation of energy-saving effects more scientific and practical. Finally, conduct large-scale experiments and field validations to further test the effectiveness and feasibility of the proposed energy management model, exploring its adaptability and implementation pathways in various types of buildings. This will provide a basis and reference for future energy-saving policies and green building development.

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